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THE MP-SEM-IPS IMAGE ANALYSIS SYSTEM

W. PETRUK

CANMET
Canada Centre for Mineral and Energy Technology
Centre canadien de la technologie des minéraux et de l'énergie

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W. Petruk

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THE MP-SEM-IPS- IMAGE ANALYSIS SYSTEM

by

W. Petruk

ABSTRACT

Image analysis is a technique for determining mineral quantities, grain size distributions, grain orientations, mineral intergrowths, mineral associations, and degrees of alteration of minerals in rocks and ores. It is performed by analysing images of polished or thin sections of the material under study. To be universally applicable to mineralogical and geochemical studies the image must be a faithful reproduction of the material, and each mineral displayed in it must be distinct enough to be discriminated and automatically identified during analysis. An image analysis system that meets these requirements was developed in the Process Mineralogy Section at CANMET by interfacing a Jeol 733 microprobe, A Tracor Northern 2000 energy dispersive X-ray analyser (EDXA), and a Kontron SEM-IPS image analyser with two-way communication between all units. The analytical procedure involves transferring a backscattered electron image (BSE) from the microprobe to the image analyser and discriminating the minerals on the basis of their grey levels in the image. If the grey level of two or more minerals is too close for discrimination, the minerals are identified by scanning each grain with the electron beam of the microprobe under control of the image analyser, and analysing the grains with the EDXA. To perform the analysis, a binary image is produced for each mineral displayed in the BSE image and prepared for analysis by using routines such as erosion, dilation, boolean operation, markobject, image enhancement, and binary thinning. The binary images are analysed and the data are classified, summarized, and output in simple tables and graphs.

LE SYSTÈME D'ANALYSE D'IMAGE MP-SEM-IPS

par

W. Petruk

RÉSUMÉ

La technique d'analyse d'image permet de déterminer, entre autres, les quantités de minéraux, la distribution granulométrique, les orientations des grains, les intercroissances et les associations minérales, et le degré d'altération des minéraux contenus dans les roches et les minerais. Cette technique est réalisée par l'analyse d'images d'une section polie ou d'une section fine des matériaux étudiés. Afin d'être applicable aux études minéralogiques et géochimiques, l'image détectée doit être une reproduction fidèle du matériau, et chaque minéral doit être suffisamment distinct sur l'image saisie pour permettre leur séparation et identification automatique au cours de l'analyse. Un système d'analyse d'image qui satisfait ces exigences a été mis au point au CANMET dans la Section de la minéralogie appliquée en interfaçant une microsonde Jeol 733, un analyseur à rayons X en dispersion d'énergie (EDXA) et un analyseur d'image Kontron SEM-IPS avec communication à deux-voies entre les unités. Les méthodes d'analyse utilisées permettent de transférer l'image électronique rétrodiffusée (BSE) de la microsonde à l'analyseur d'image et de détecter les minéraux d'après les différents niveaux de gris sur l'image. Si le niveau de gris de deux ou plusieurs minéraux est trop semblable pour permettre la détection des minéraux, l'identification de ces derniers est effectuée en dirigeant le faisceau d'électrons de la microsonde avec l'analyseur d'image pour balayer chaque grain, et en analysant ces grains à l'aide de l'EDXA. Pour réaliser l'analyse, une image binaire est produite pour chaque minéral détecté sur l'image électronique rétrodiffusée. L'image est ensuite préparée pour analyse à l'aide de procédés courants tels que l'érosion, l'allongement, l'opération booléenne, le repérage d'objet, la mise en valeur de l'image et l'amincissement binaire. Enfin, les images binaires sont analysées et les données obtenues sont classées, résumées et représentées sous forme de tableaux et de graphiques simples.

CONTENTS

	Page
ABSTRACT	i
RÉSUMÉ	iii
INTRODUCTION	1
FEATURES OF THE MP-SEM-IPS AUTOMATIC IMAGE ANALYSIS SYSTEM	2
General Operation of System	2
Image Input	3
Mineral Identification	4
Discrimination of Minerals	5
Grain Boundary Reconstruction	6
Analysis	6
Mineral quantities	6
Size distributions	6
Aspect ratios	7
Grain Orientations	7
Mineral Associations	7
Percentage of mineral occurring as inclusions	8
Separating Interconnecting Grains	8
Analyses Associated With Mineral Dressing	8
CONCLUDING REMARKS	9
REFERENCES	10

FIGURES

No.		
1.	The MP-SEM-IPS image analysis system in the Process Mineralogy Section at CANMET	13
2.	Images on image analyser	14
3.	X-ray spectrum for orthoclase on screen of EDXA	15
4.	Screen of image analyser showing the sub-routines that are available under the PARAMETERS program	15

CONTENTS (cont'd)

No.		Page
5.	Printout of computer routine to calculate the relative peak intensities for Na, Mg, Al, Si, K, Ca, Ti, and Fe in silicate minerals reference file	16
6a.	Mineral standards in the silicate reference file	17
6b.	Relative peak intensities for each element obtained by measuring albite	17
6c.	The relative peak intensities shown in Figure 6B are combined into a reference file of element peaks (vertical columns) for minerals listed in Figure 6A (horizontal lines)	17
6d.	Identification of albite and quartz of Figures 2B and 2C	17
7a.	An unfiltered digitized image for quartz plus albite showing artifacts from other minerals	18
7b.	Enhanced binary image of Figure 7A	18
8.	Detection of compositional zones in an allanite grain where the grey levels for the zones are close and overlap	19
9a.	BSE image of massive pyrite with interstitial sphalerite, transferred to the image analyser	20
9b.	Detected binary image of pyrite	20
9c.	Grain boundaries are reconstructed	20
10.	Sample of data output from image analyser showing mineral quantities, in area per cent	21
11.	Graphic output from the image analyser for the orthoclase shown in figure 2G	22
12.	Standard output of data that was used to plot Figures 11A, 11B and 11C	23
13.	An example of output of data used for double classification	24
14.	Procedure to obtain mineral associations	25
15.	Inclusions in a host mineral	26
16.	Separating interconnecting grains	27
17.	Classification of particles into categories that contain 0-10, 10-20, 20-30, etc. % mineral of interest	28

INTRODUCTION

Image analysis is a technique that can be used to determine mineral quantities, grain size distributions, grain orientations, mineral intergrowths, mineral associations, and degree of alteration of minerals in rocks, ores, and broken materials. When the analysis is performed in the automatic mode, the minerals must be automatically identified before parameters can be measured. The technique involves analysing an image of a polished or thin section of the material, by (1) producing an image with an optical microscope, scanning electron microscope (SEM), or microprobe and transferring it to an image analyser, (2) by digitizing the image, (3) by processing the digitized image and measuring appropriate parameters, and (4) by classifying and summarizing the data and outputting it in a simple format.

The combination of the imaging instrument plus the image analyser will be referred to in this paper as an image analysis system. To be universally applicable to mineralogical and geochemical studies, the image analysis system must have the capability of discriminating and identifying every mineral in every field of view, and of automatically performing the required analysis. Until 1980 the optical microscope was the imaging instrument, and the image was transferred to the image analyser via a black and white TV camera. Unfortunately many minerals cannot be discriminated from each other in a black and white image produced with an optical microscope. An interface that will transfer a colour image from an optical microscope to the image analyser was released for the market in early 1986. This development will undoubtedly solve the discrimination problem between some minerals, but it will still be impossible to discriminate many others. Consequently an image produced with an optical microscope does not have the potential of being universally applicable to mineralogical studies. By contrast most minerals can be discriminated from each other by their grey levels in the backscattered electron (BSE) image produced with a scanning electron microscope (SEM) or microprobe. Furthermore, if several minerals in the assemblage have the same grey level and cannot be so discriminated, they can be identified by automatically scanning each particle with the SEM and analysing it with the energy dispersive X-ray analyser (EDXA). An automatic image analysis system for applications in mineralogy should, therefore, consist of a

SEM, an EDXA, and an image analyser interfaced in such a way that there is two-way communication between all units. In addition, the analysis must be performed in the automatic mode since many grains need to be analysed. Unfortunately only a few image analysers have an interface that permits the required two-way communications. Furthermore, only the fully-equipped image analysers have the necessary hardware and software for performing the various analyses that may be required during mineralogical and geochemical studies.

In the Process Mineralogy Section of the Mineral Processing Laboratory at CANMET we developed an automatic image analysis system by interfacing a JEOL 733 microprobe, a Tracor Northern 2000 EDXA, and an SEM-IPS Kontron image analyser with two-way communication between all units. We refer to the system as the MP-SEM-IPS image analysis system (Fig. 1). A description of the system is given in this paper as an example of a fully equipped automatic image analysis system.

FEATURES OF THE MP-SEM-IPS AUTOMATIC IMAGE ANALYSIS SYSTEM

GENERAL OPERATION OF SYSTEM

During set-up for analysis a BSE image is obtained on the microprobe and transferred to the image analyser via an interface (Fig. 2). Each mineral is discriminated on the basis of its grey level in the image (Figs. 2B, 2F-2H), and a separate binary image is produced for the mineral. Each mineral is identified off-line with the EDXA (Fig. 3). If it is found that several minerals have the same grey level, they are identified during analysis by scanning the particles from the image of the multi-mineral grey level (Fig. 2B) with the electron beam. Each particle displayed in this grey level is therefore individually identified (Fig. 2C). Images of mineral grains that have been identified, on the basis of grey level, as well as by scanning individual particles are stored in a separate image memory for each mineral (Figs. 2D-2H). The grains in each image memory are then analysed to determine the required properties, such as mineral quantities, size distributions, etc., and the data are output in appropriate tables and graphs. When the analysis of a field is completed the sample is automatically moved to a new field and the process is repeated. Generally

enough fields are analysed to measure about 5000 particles. The operation is performed unattended, but an operator needs to be present because a complex field may introduce an error that will cause the analysis to stop and wait for manual instruction.

The image analysis system has several hundred image analysis programs (Fig. 4). The analysis is performed by stringing appropriate image analysis programs in series to build an operator's program for the required task. The system operates in such a manner, that during set-up, image analysis programs are entered into the operator's program whenever they are tried. When a workable operator's program has been developed, the operator can save it to disk, edit it, and recall it as required.

IMAGE INPUT

For automatic image analysis, it is of utmost importance that the image transferred to the image analyser be a faithful reproduction of the image under study, and that each mineral displayed in it can be discriminated. The grey levels of minerals in the BSE image from an SEM or microprobe relate to the average atomic number of the minerals, with the lowest atomic number mineral being darkest grey, and the highest atomic number mineral being white (Fig. 2A). The minerals can therefore be discriminated from each other by their grey level in the BSE image, and identified. Another desirable feature of the BSE image is that, unlike the image from the optical microscope, the grey level for each mineral stays constant as the sample is moved from field to field, and as the magnification is changed, providing that the accelerating voltage, the beam current on the Faraday cup, and the amplifier brightness and contrast from the BSE detector are constant. Therefore, a primary requisite is that the SEM or microprobe have meters for monitoring these conditions. All the meter readings must remain constant during the period of analysis, which could be several hours. To maintain a constant current, a beam stabilizer is a necessary module on a microprobe or SEM.

The window for the grey level can be modified during set-up by adjusting the BSE amplifier brightness and contrast on the microprobe or SEM. A narrow window permits good discrimination between minerals, but the window needs to be wide enough to include all the minerals that need to be analysed. It has been found that quartz can be readily discriminated from

orthoclase in an image produced at a setting of 20kv and 15 na, with a window that is wide enough to include all the silicate and metallic minerals in a base metal ore. By contrast quartz cannot be discriminated from albite on the basis of grey level because both minerals have nearly the same average atomic number, 10.8 and 10.7 respectively.

MINERAL IDENTIFICATION

It is possible to discriminate about fifteen different phases in the BSE image that has been transferred to the image analyser. The mineral represented by each grey level can be identified off-line by focusing the electron beam of the microprobe on a representative particle. An X-ray spectrum is collected from the particle and identified manually with the EDXA (Fig. 3). A mineral name is then assigned to particles within each grey level, and this mineral identity remains constant as long as the operating conditions on the microprobe remain constant. If it is found that more than one mineral is represented by a particular grey level, each particle in the multi-mineral image (Fig. 2B) is scanned automatically with the X-ray beam and identified on the basis of its chemical composition. The above-mentioned albite and quartz are discriminated and identified (Fig. 2C) in this manner. Before scanning the particles in the multi-mineral image it is recommended that the image be prepared for particle scanning by eroding several pixels from the outer layers of the grain images. The eroded grain images form the scan control boundaries for the electron beam. These boundaries make the scan areas slightly smaller than the grain areas and thereby reduce the probability of detecting elements from neighbouring minerals during scanning.

The process of automatically identifying particles by scanning with an X-ray beam requires setting a number of conditions. The first condition is setting windows on the EDXA to define the elements that will be used for identifying the minerals. The second is writing a computer routine that will label the element peaks and calculate the relative peak intensities (Fig. 5). It is noteworthy that mineral compositions are normally determined by counting the X-rays from each particle for a set period of time. The Kontron classification system, however, works by scanning each particle at a speed defined by the operator. Therefore it will take a longer period of time to scan a large particle than a small particle. Consequently a

relative peak intensity that is independent of scan time is calculated for each peak in each window (Fig. 5). The third condition is building a reference mineralogy file which is prepared by scanning mineral standards to obtain relative peak intensities in each window for each reference mineral (Fig. 6).

DISCRIMINATION OF MINERALS

The transition from one grey level to another in a multi-level BSE or optical microscope image occurs over a distance of one to several pixels, and this is reflected in the detected binary image, which is the image that is analysed. Consequently, the initial binary image is a poor representation of the area covered by the grey level in the original BSE image. The transitions are referred to as halo effects, artifacts from other minerals, electronic noise, overlapping grey levels, etc. (Fig. 7A). The digitized binary image can, however, be filtered and enhanced so that the binary image for the mineral is an exact or nearly exact representation of the grey level in the original BSE image (Fig. 7B). The enhancement is achieved by a variety of methods, including an erosion-dilation technique to remove small unwanted binary features and a restoration technique to restore the remaining features to their original size and shape. For an exact overlay of binary image on the original image, Boolean and Markobject operations are used in conjunction with the erosion-dilation technique. These two operations retain the boundaries of the particles in the original image; by contrast the erosion-dilation technique, used alone, produces computer-generated boundaries which will not be the same as the boundaries in the original BSE image.

If a mineral is poorly detected because of overlap of grey level with another mineral, the detected image can be enhanced to represent the mineral. This is done by a routine that determines the density of pixels in the detected binary image and creates mineral outlines (Figs. 8A-8H). This computer-generated outline is not a true outline of the mineral (Figs. 8C, 8E, 8G and 8H), but is a relatively accurate representation. The enhanced image of each mineral is then stored in a separate image memory.

GRAIN BOUNDARY RECONSTRUCTION

In some instances it may be necessary to determine the size distributions or orientations of grains in a massive piece of mineral. This operation requires that each grain be outlined. Unfortunately the grain boundaries are generally absent in an image obtained from a polished or thin section of a mineral mass. However, incipient outlines of the mineral grains may be seen (Fig. 9A). It is possible to reconstruct the grain boundaries in the image of the mineral from these incipient outlines by combining the erosion, dilation, boolean operation, pixel density, binary thinning, and markobject operations into an appropriate operator's program (Figs. 9B and 9C).

ANALYSIS

Mineral Quantities

Mineral quantities can be determined by measuring either the total chord lengths, or the total surface areas covered by the particles in binary images of the minerals (Fig. 10). The measurement can be directly converted to the relative volume percent for each mineral since the stereological relationship is that the relative chord length or the relative surface area is equal to relative volume percent. The relative mineral volumes can be converted to relative weight percent by using the specific gravity for each mineral.

Size Distributions

Several types of size distributions can be performed by using different parameters and making appropriate measurements for each particle in the binary images. One involves measuring the intercept lengths across the particles (Figs. 11A and 12A), and another the surface areas of the particles. When the surface area of the particle is measured, the size distribution can be reported on the basis of the number of particles in each size range (Figs. 11C and 12C), or the area percent covered by the particles in each size range (Figs. 11B and 12B). The latter type provides a size distribution that can be converted to volume percent and hence to weight percent. The sizes that can be used to define the particles are maximum, minimum, mean, equivalent circle, and equivalent square diameters. Equivalent circle and equivalent square diameters are determined by measuring the surface area

of the particles and calculating the diameter in question. It is noteworthy that the mean diameter is nearly equal to the equivalent circle diameter, whereas the equivalent square diameter is nearly equal to the size of particle that would pass through screen openings.

Aspect Ratios

The aspect ratios of the particles in the binary images can be determined by using an algorithm that calculates the values for the maximum diameter divided by the minimum diameter. The grains can be classified as aspect ratio vs grain size (Figs. 11D and 11E).

Grain Orientations

The angle between horizontal and the inclinaion of the maximum diameter is a standard measurement that is available on most image analysers. This measurement can be made for all particles in each binary image; and as pointed out in the discussion on size distributions the measurement can be based on either number of individuals at each orientation or area percent covered by particles of each orientation (Fig. 11F). In addition the results can be classified as grain sizes vs grain orientation (Figs. 11G and 13).

Mineral Associations

To determine mineral associations it is necessary to prepare the binary images for analysis. The following example is given to show the logic. The problem is to determine the percentage of orthoclase from Fig. 2G that is adjacent to quartz and albite from Figures 2D and 2E respectively (Fig. 14A). To solve this problem it is necessary to find the common boundaries between the orthoclase and albite and the orthoclase and quartz (Fig. 14B). The percentage of orthoclase touching the orthoclase-albite boundary is the percentage of orthoclase associated with albite (Fig. 14C), and the percentage touching the orthoclase-quartz boundary is the percentage associated with quartz (Fig. 14D). As before, size distributions and other parameters of the associated grains can be determined.

Percentage of Mineral Occurring as Inclusions

To determine the percentage of mineral occurring as inclusions in another mineral it is also necessary to prepare the binary images for analysis by finding the common grain boundaries between the different minerals. The mineral occurring as inclusions must have a common boundary with the host mineral but not with any other mineral. The procedure is to first select those grains that have a common boundary with the host mineral, then reject any that have a common boundary with another mineral. The remaining grains are inclusions (Figs. 15B and 15C). The image of the inclusions can be stored in a separate image memory and measured and classified as required.

SEPARATING INTERCONNECTING GRAINS

In many instances large grains in a rock or ore may be interconnected with veinlets. It may be desirable to find the relative quantities and sizes of the large grains and the relative quantities and widths of the interconnecting veinlets. To do this, it is necessary to modify the binary image by separating the large grains from the interconnecting veinlets and saving the two images in separate image memories (Fig. 16). It is noted that Figure 16 also shows narrow veinlets that do not interconnect the large grains. The procedure for separating the large grains from the interconnecting veinlets is done by using the erosion, dilation, boolean operation, markobject, binary thinning, and image enhancement techniques in an appropriate operator's program.

ANALYSES ASSOCIATED WITH MINERAL DRESSING

Analyses associated with mineral dressing generally involve studying crushed mill products. The most common requirement is to measure the percentage of mineral that is present as free grains and to classify the unliberated grains. The procedure is the same as in determining mineral associations. A common boundary is looked for. If a mineral grain does not have a common boundary with any other mineral, it is assumed to have been liberated during grinding and is a free grain. The percentage of mineral that occurs as free grains, and the size distributions of the free grains can be measured. The unliberated grains are studied in more detail by recombining the binary image of the unliberated grain with the binary images of other minerals to reconstruct the host particle. The percentage that the

unliberated grain contributes to each host particle and the size of the host particle are measured. The particles are then classified as containing different amounts of the unliberated mineral. The data are output on a percentage basis as quantity of mineral of each size and in each class of particle (Fig. 17).

CONCLUDING REMARKS

This paper is intended to give the reader an insight into the scope of image analysis and into the capabilities of image analysis systems.

The most important considerations with respect to image analysis applied to mineralogical studies are that the digitized image be a faithful reproduction of an image of the material under study, and that the image analysis system have the capabilities of performing the required analyses. In general, when an image is obtained from an optical microscope, many minerals cannot be discriminated from each other, and hence cannot be digitized. By contrast most minerals can be discriminated and digitized in a BSE image from an SEM or microprobe. Therefore, a universal image analysis system for studying minerals must use an SEM or microprobe as the imaging instrument.

Nearly all image analysers on the market have the capabilities of determining mineral quantities, size distributions, and obtaining measurements for fractal analysis. However, only the fully equipped image analysers have the required hardware and software for performing the other analyses referred to in this report; particularly, the analyses that involve obtaining a common grain boundary. Furthermore, many of the small image analysers have limited image enhancement capabilities, however, in many instances maximum image enhancement is required. Consequently, because of the wide range of capabilities of image analysers (Petruk, 1986), a careful survey of one's needs, and of image analyser capabilities, must be made before an image analysis system is purchased.

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Petruk, W. (1985); "Image analysis measurements and data presentation for mineral dressing applications"; Applied Mineralogy; eds. W.C. Park, D.M. Hausen and R.D. Hagni; pp. 127-140; AIME/TMS; New York, N.Y.

Petruk, W. (1986); "Image analysis: an overview of developments"; CANMET Report 86-4E; CANMET, Energy, Mines and Resources Canada; Ottawa, Canada.

FIGURES

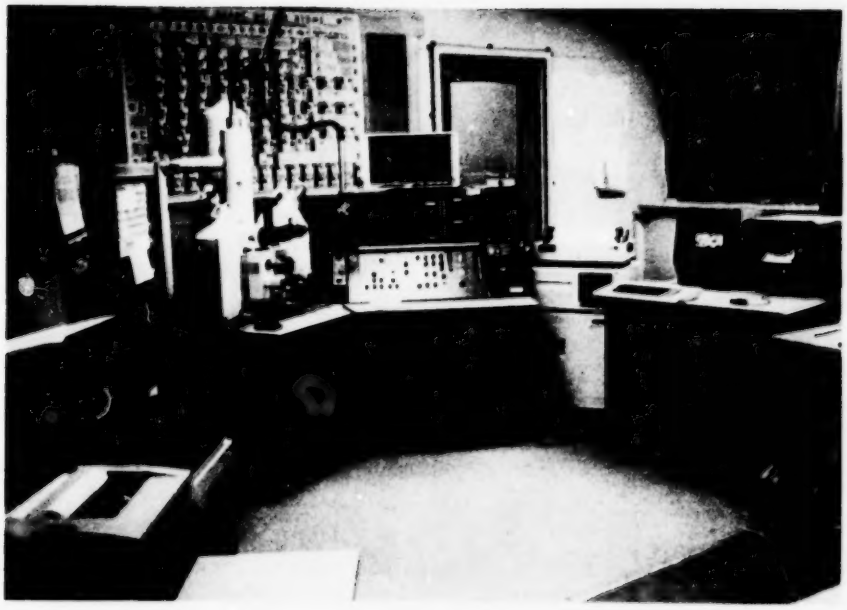

Fig. 1. The MP-SEM-IPS image analysis system in the Process Mineralogy Section at CANMET. It is composed of a JEOL 733 microprobe (centre), a Tracor Northern 2000 (left), and a Kontron SEM-IPS image analyser (right).

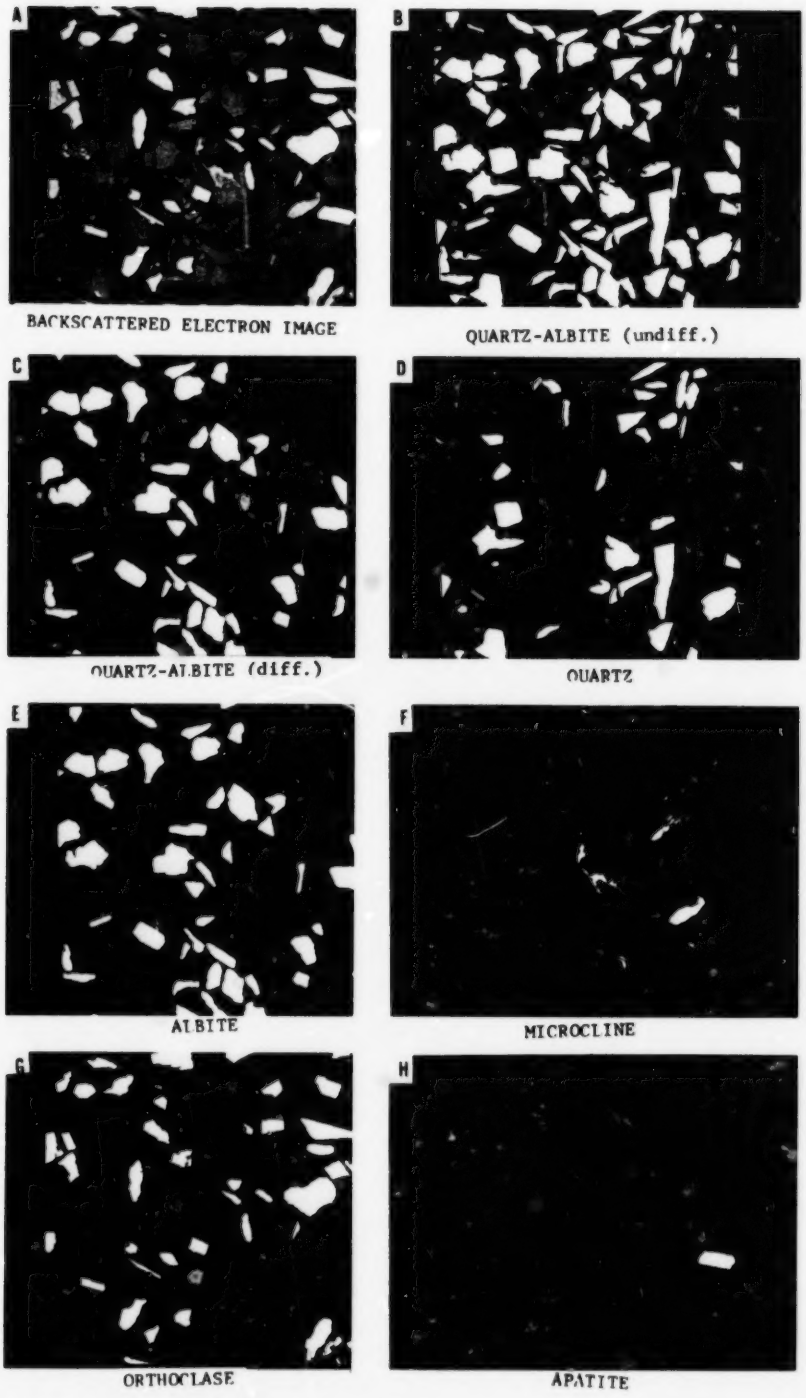

Fig. 2. Images on image analyser:

(A) Electron backscattered (BSE) image transferred to the image analyser. The grey grains are quartz and albite, the medium grey are microcline, the light grey are orthoclase, and the white are apatite.

(B) Binary image of quartz plus albite (undifferentiated).

(C) The quartz and albite of image 2B have been identified with the EDXA (differentiated). The quartz is dark grey and albite is white.

(D-H) Binary images: D = quartz, E = albite, F = microcline, G = orthoclase, and H = apatite.

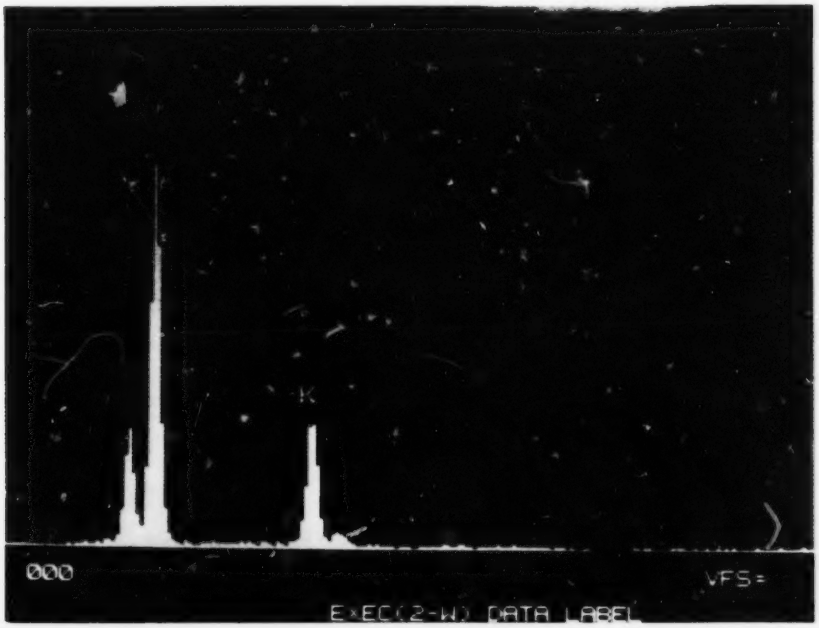

Fig. 3. X-ray spectrum for orthoclase on screen of EDXA

Fig. 4. Screen of image analyser showing the sub-routines that are available under the PARAMETERS program. The sub-routine AREA has been activated. The last three lines in the middle screen are variables in the AREA subroutine. The right side of the screen shows a string of commands which is the operator's program.

```
RCL 01,RCL 02,+,RCL 03,+,RCL 04,+,RCL 05,  +,
RCL 06,+,RCL 07,+,RCL 08,+
STORE 01
RCL 01,RCL 01,0.1,+,/,STORE 01
RCL 02,RCL 01,0.1,+,/,STORE 02
RCL 03,RCL 01,0.1,+,/,STORE 03
RCL 04,RCL 01,0.1,+,/,STORE 04
RCL 05,RCL 01,0.1,+,/,STORE 05
RCL 06,RCL 01,0.1,+,/,STORE 06
RCL 07,RCL 01,0.1,+,/,STORE 07
RCL 08,RCL 01,0.1,+,/,STORE 08
END
STORE 01=# CNT01
STORE 02=# CNT02
STORE 03=# CNT03
STORE 04=# CNT04
STORE 05=# CNT05
STORE 06=# CNT06
STORE 07=# CNT07
STORE 08=# CNT08
STORE 01=NA KA
STORE 02=MG KA
STORE 03=AL KA
STORE 04=SI KA
STORE 05=K KA
STORE 06=CA KA
STORE 07=TI KA
STORE 08=FE KA
STORE 09=CLASS
END
```

Fig. 5. Printout of computer routine to calculate the relative peak intensities for Na, Mg, Al, Si, K, Ca, Ti, and Fe in silicate minerals reference file. The term CNT refers to counts in each element window, and the routine at the top is the procedure for processing the counts.

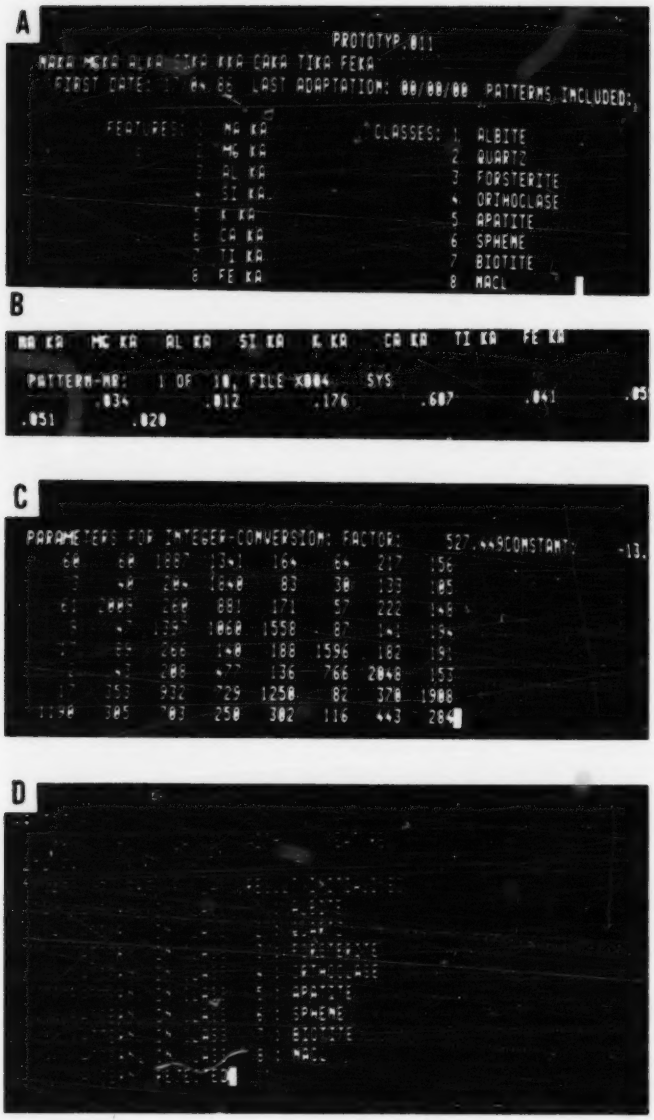

Fig. 6. (A) Mineral standards in the silicate reference file.
(B) Relative peak intensities for each element obtained by measuring albite.
(C) The relative peak intensities shown in Figure 6B are combined into a reference file of element peaks (vertical columns) for minerals listed in Figure 6A (horizontal lines). This file is used to identify unknown silicates.
(D) Identification of albite and quartz of Figures 2B and 2C.

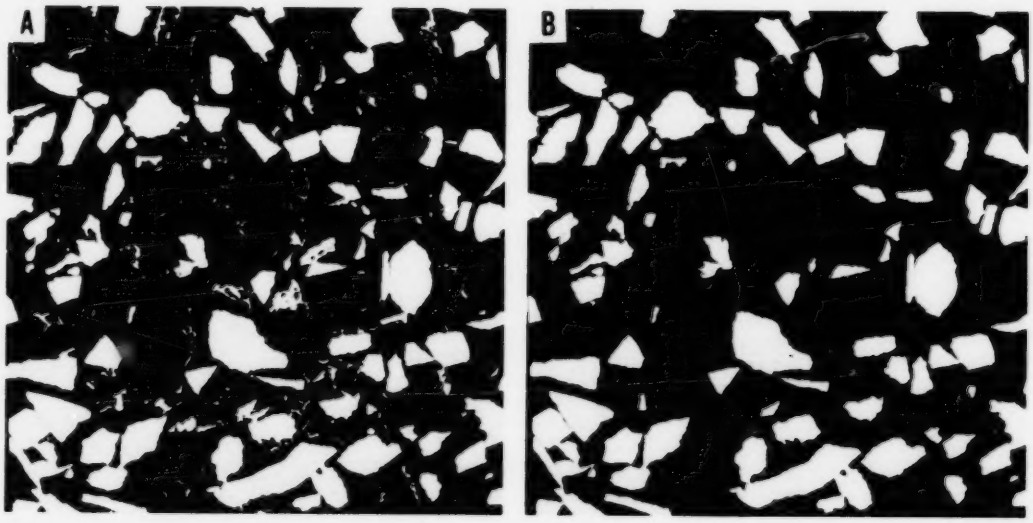

Fig. 7A. An unfiltered digitized image for quartz plus albite showing artifacts from other minerals.

7B. Enhanced binary image of Figure 7A. It was enhanced by erosion to remove small unwanted features and by restoration to bring the grains to the original grain sizes and shapes by using the markobject operation.

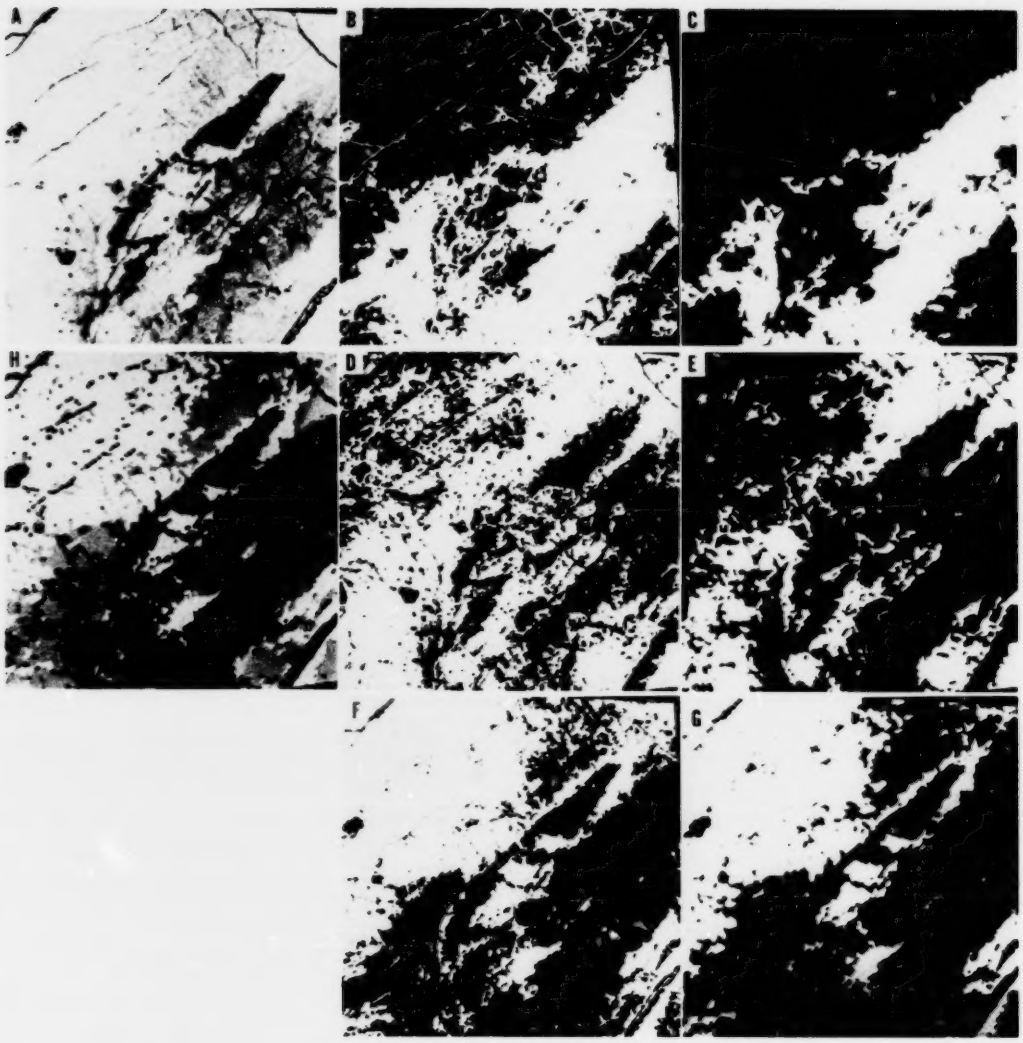

Fig. 8. Detection of compositional zones in an allanite grain where the grey levels for the zones are close and overlap.
(A) BSE image transferred to image analyser.
(B) Detection of darkest grey zone plus artifacts from other grey zones.
(C) Enhanced binary image of Figure 8B using the density of pixels routine.
(D) Detection of second zone plus artifacts from other zones.
(E) Enhanced binary image of Figure 8D using the density of pixels routine.
(F) Detection of third zone plus artifacts.
(G) Enhanced binary image of third zone.
(H) Binary images 8C, 8E and 8G combined. For presentation, image 8C was given an artificial dark grey colour, image 8E a light grey, and image 8G white.

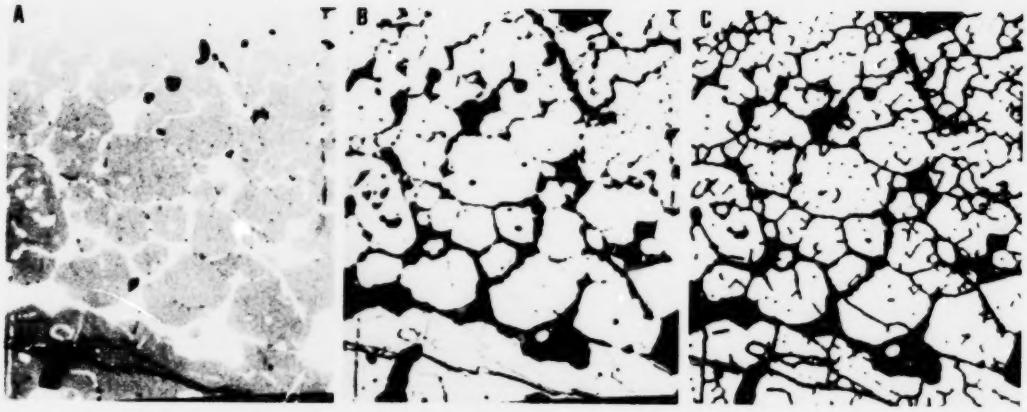

Fig. 9A. BSE image of massive pyrite with interstitial sphalerite, transferred to the image analyser.
9B. Detected binary image of pyrite.
9C. Grain boundaries are reconstructed. Incipient lines in Figure 9B were used to reconstruct grain boundaries.

```
table #   1 SUMS
variable z: FAREA
variable x: FAREA
variable y: CHANNEL

          0.00        .900E+06

     0.00        0.00        0.00        0.00
1.000
     0.00        27.4        0.00        27.4
2.00
     0.00        38.1        0.00        38.1
3.00
     0.00        3.55        0.00        3.55
4.00
     0.00        29.9        0.00        29.9
5.00
     0.00        1.03        0.00        1.03

     0.00       100.0        0.00       100.0
```

Fig. 10. Sample of data output from image analyser showing mineral quantities, in area per cent (last column). The data are for the areas of minerals in the images shown in Figures 2D-2H. No. 1 = quartz, 2 = albite, 3 = microcline, 4 = orthoclase and 5 = apatite.

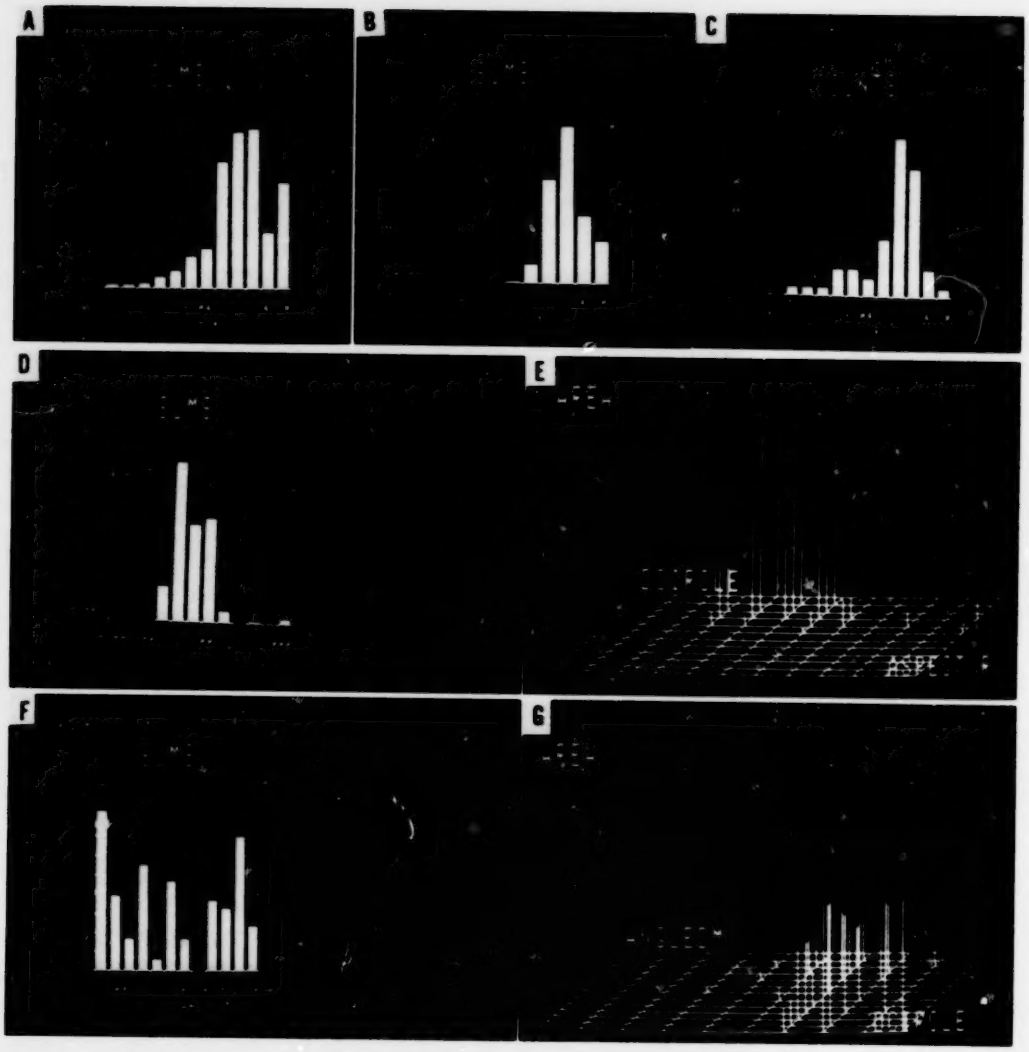

Fig. 11. Graphic output from the image analyser for the orthoclase shown in figure 2G.

(A) Chord size distribution.
(B) Size distribution using the surface area of each grain.
(C) Grain counts for grains of each size.
(D) Distribution of aspect ratio, using the surface area of each grain to determine the relative quantity of mineral that is represented by grains which have a certain aspect ratio.
(E) Double classification of aspect ratio vs grain diameter using the surface area of each grain to define the relative amount in each category.
(F) Distribution of orientation of maximum grain diameter with respect to horizontal. Surface areas of mineral grains were used to determine the relative quantity of mineral in each category.
(G) Double classification of grain orientation vs grain diameter.

table # 4 SUMS
variable z: CHORD
variable x: CHANNEL
variable y: CHORD

	0.00	.900E+04	
4.61	.763	.345E-37	0.00	.763
6.52	.773	0.00	0.00	.773
9.22	.869	0.00	0.00	.869
13.0	.876	0.00	1.01	1.89
18.4	2.54	0.00	.773E-01	2.61
26.0	1.61	1.52	1.61	4.74
36.8	5.54	0.00	.142	5.68
52.0	8.96	3.19	5.28	17.4
73.6	18.5	0.00	2.65	21.2
104.	12.3	3.47	5.84	21.6
147.	4.80	.177	2.90	7.87
	5.87	4.23	4.49	14.6
	63.4	12.6	24.0	100.

table # 1 SUMS
variable z: AREA
variable x: AREA
variable y: DCIRCLE

	0.00	.900E+05	
4.61	0.00	0.00	0.00	0.00
6.52	0.00	.162E-01	0.00	.162E-01
9.22	0.00	.260E-01	0.00	.260E-01
13.0	0.00	.455E-01	0.00	.455E-01
18.4	0.00	.237	0.00	.237
26.0	0.00	.695	0.00	.695
36.8	0.00	.893	0.00	.893
52.0	0.00	5.38	0.00	5.38
73.6	0.00	26.1	0.00	26.1
104.	0.00	38.6	0.00	38.6
147.	0.00	17.1	0.00	17.1
	0.00	10.8	0.00	10.8
	0.00	100.	0.00	100.

table # 2 COUNTS
variable z: AREA
variable x: AREA
variable y: DCIRCLE

	0.00	.900E+06	
4.61	0.00	3.00	0.00	3.00
6.52	0.00	4.00	0.00	4.00
9.22	0.00	1.000	0.00	1.000
13.0	0.00	4.00	0.00	4.00
18.4	0.00	7.00	0.00	7.00
26.0	0.00	17.0	0.00	17.0
36.8	0.00	18.0	0.00	18.0
52.0	0.00	12.0	0.00	12.0
73.6	0.00	17.0	0.00	17.0
104.	0.00	13.0	0.00	13.0
147.	0.00	3.00	0.00	3.00
	0.00	1.000	0.00	1.000
	0.00	100.0	0.00	100.0

Fig. 12A-12C. Standard output of data that was used to plot Figures 11A, 11B and 11C.

table 0 2 SUM0
variable z: AREA
variable x: ASPECT R
variable y: DCIRCLE

	0.00	.500	1.000	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.00		
4.61	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.162E-01	.16
9.22	0.00	0.00	0.00	0.00	.268E-01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.268
13.0	0.00	0.00	0.00	0.00	.455E-01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.455
18.4	0.00	0.00	0.00	0.00	.166	0.00	0.00	0.00	.714E-01	0.00	0.00	0.00	.237
26.0	0.00	0.00	0.00	0.00	.244	.221	.231	0.00	0.00	0.00	0.00	0.00	.695
36.8	0.00	0.00	0.00	0.00	0.00	0.00	.458	0.00	0.00	0.00	0.00	.435	.893
52.0	0.00	0.00	0.00	.981	.640	0.00	1.03	1.69	0.00	1.04	0.00	0.00	5.38
73.6	0.00	0.00	0.00	4.75	8.65	4.47	5.61	1.40	0.00	0.00	0.00	1.26	26.1
104.	0.00	0.00	0.00	2.94	16.7	12.8	6.15	0.00	0.00	0.00	0.00	0.00	38.6
147.	0.00	0.00	0.00	0.00	0.00	5.86	11.3	0.00	0.00	0.00	0.00	0.00	17.1
	0.00	0.00	0.00	0.00	10.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.8
	0.00	0.00	0.00	8.66	37.3	23.4	24.8	3.09	.714E-01	1.04	0.00	1.71	100.

Fig. 13. An example of output of data used for double classification. This data was used to plot Figures 11D (bottom line of data set, Fig. 13) and 11G (all data in Fig. 13). the data in the tables in Figures 12 and 13 are given in percent, whereas the graphs in Figure 11 were plotted from total values. The graphs were plotted from total values because higher peaks were obtained than by using percent. The relativity between the peaks is the same when the data is plotted from percent as from total values.

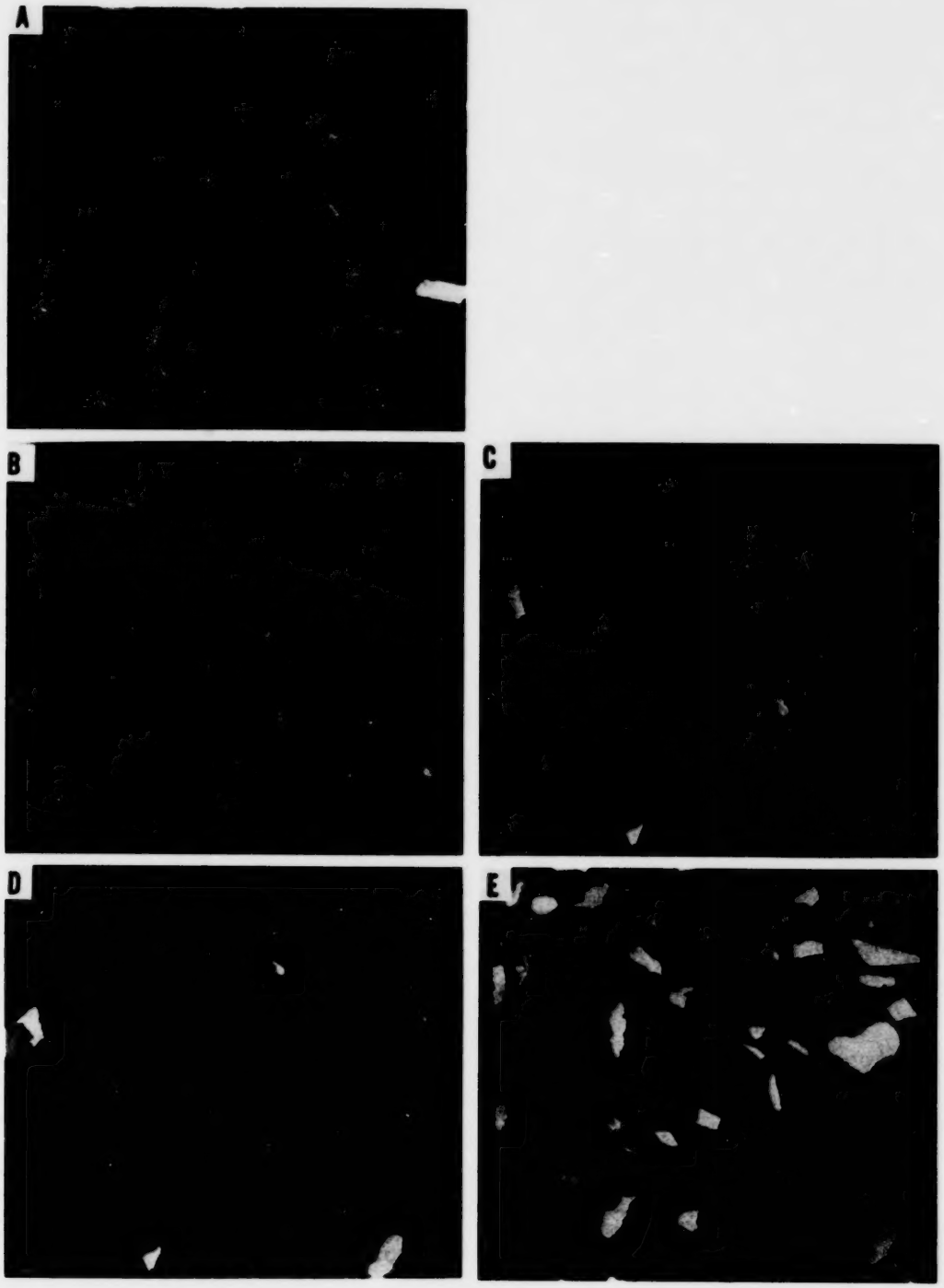

Fig. 14. Procedure to obtain mineral associations
(A) BSE image of field from Figure 2.
(B) Common boundaries between orthoclase and albite and between orthoclase and quartz.
(C) Orthoclase grains associated with albite.
(D) Combined grains showing orthoclase (white), albite (light grey) and quartz (grey).
(E) Orthoclase that is not associated with albite.

Fig. 15. Inclusions in a host mineral.
(A) BSE image of a base metal ore transferred to image analyser. It shows galena (white) in sphalerite (light grey), chalcopyrite (med. grey, outlined) and pyrite (dark grey).
(B&C) Restored binary image to two shades of grey in each image: B = galena inclusions (white) in sphalerite (grey), C = galena inclusions (white) in pyrite.

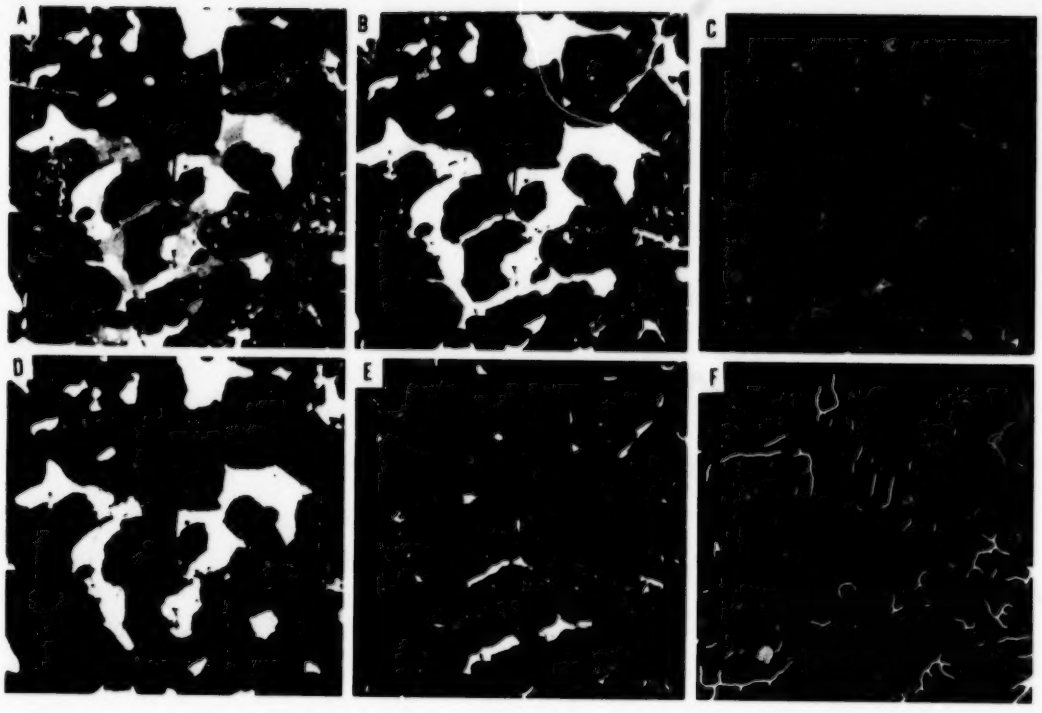

Fig. 16. Separating interconnecting grains.
(A) BSE image of a base metal ore showing sphalerite (light grey) and chalcopyrite (med. grey) in pyrite (grey).
(B) Sphalerite and chalcopyrite were detected together to produce a binary image of interconnecting large grains.
(D) Large grains are separated.
(E) Interconnecting veinlets.
(F) Narrow veinlets are isolated.
(C) Images D, E, and F are combined using artificial grey colours for each image.

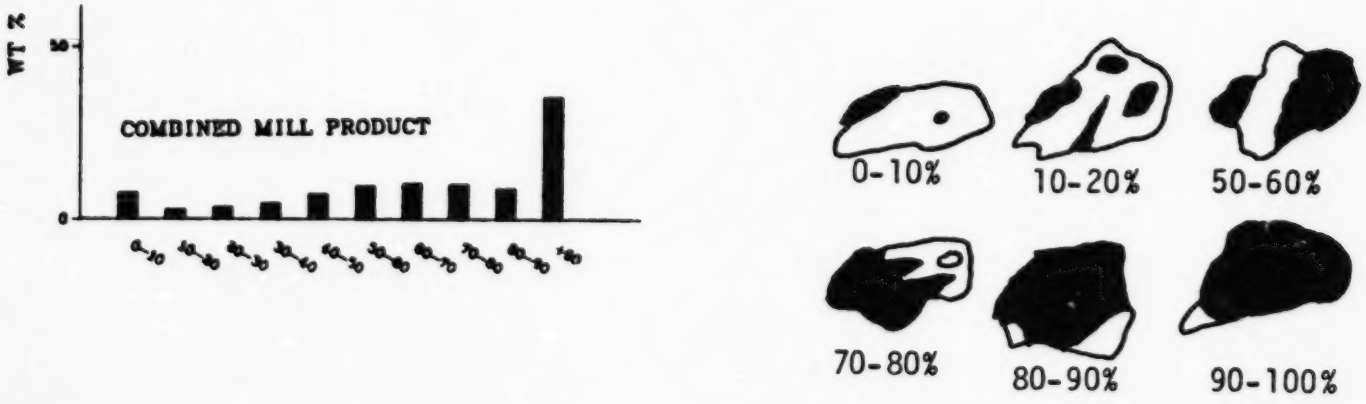

Fig. 17. Classification of particles into categories that contain 0-10, 10-20, 20-30, etc. % mineral of interest. The X-axis shows the classified particles, and Y-axis the quantity in each class (Photograph from Petruk, 1984).